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EUV Workshop, Dublin 7-9 November 2011

The EUV Laser Program at the University of Bern

Bridging the Gap Between Tools & Applications

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Outline

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- > **Gaps**
- > **Tool: The „BeAGLE“ Facility**
  - — Update on Lasing Wavelength
  - — Investigations on Conversion Efficiency
  - — Upgrade of Repetition Rate
- > **Applications: Beamlines at BeAGLE**
  - — Spectroscopy
  - — Roadmap for Imaging
  - — Roadmap for Coherent Diffraction
- > **Summary**

Gaps Yet to Bridge

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- **Beamlines Accessibility**
  - Beam-time policy bottlenecks research activity;
  - Proposal commitment: confidentiality & throughput concerns;
  - No mass production.
- **Application Requirements**
  - Multiscale;
  - Time-resolution → *Pulse duration*;
  - Selectivity → *Linewidth*;
  - Process Efficiency → *Brightness*.
- **Tool Cost-of-Ownership**

Short-wavelength Tools...

...Applications

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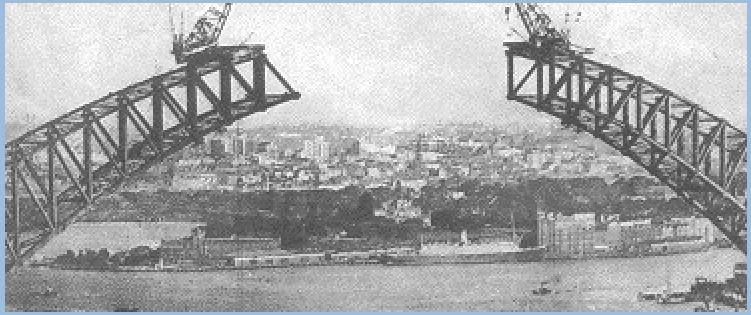

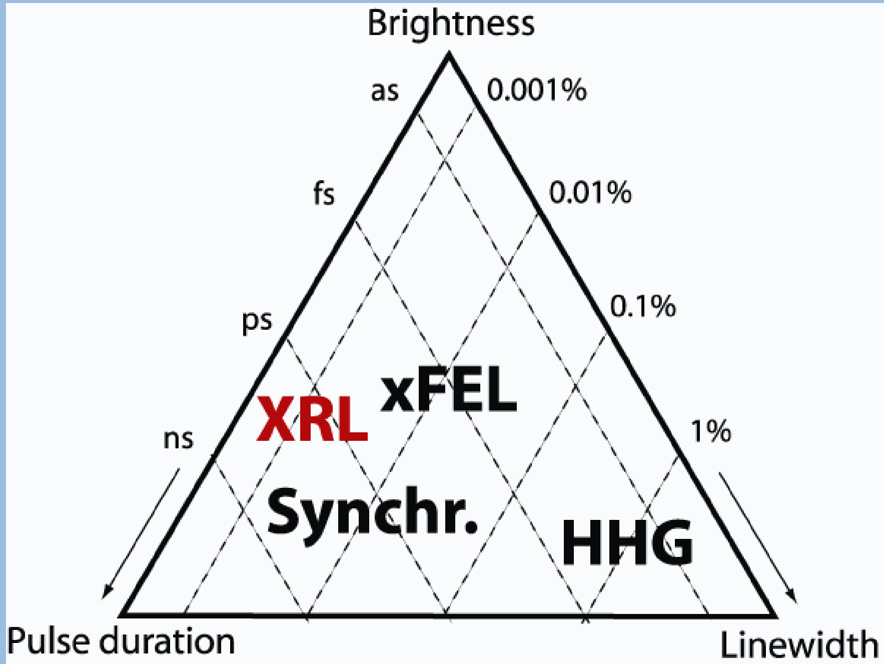

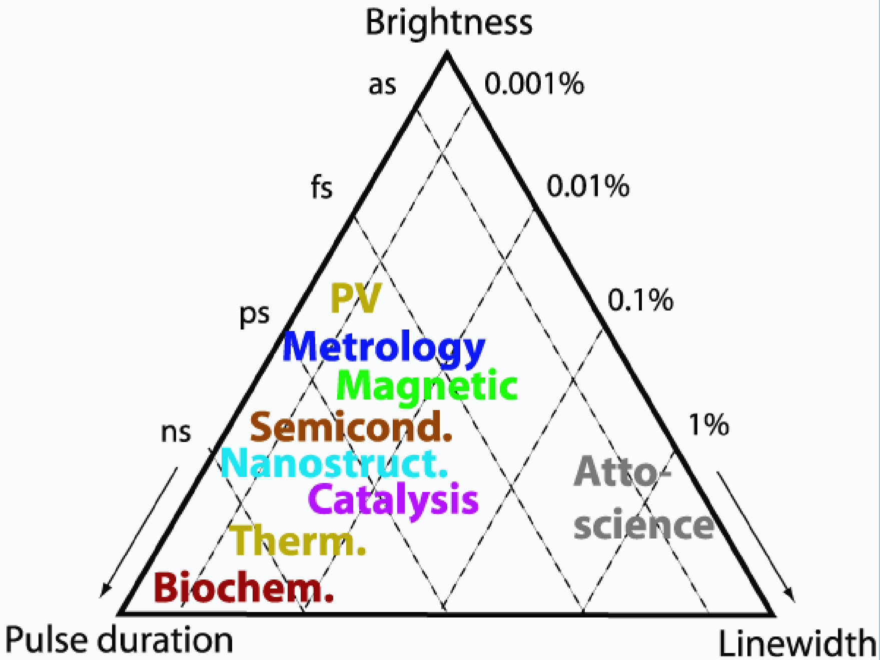

The Extreme Ultraviolet Coherent Source
(aka “X-ray Laser”)

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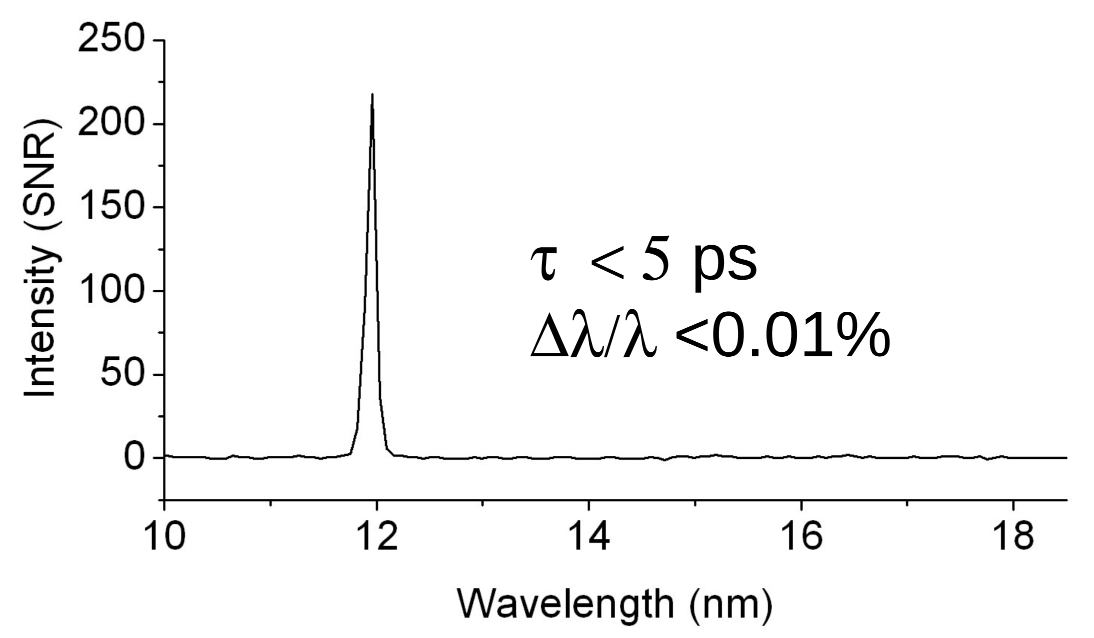

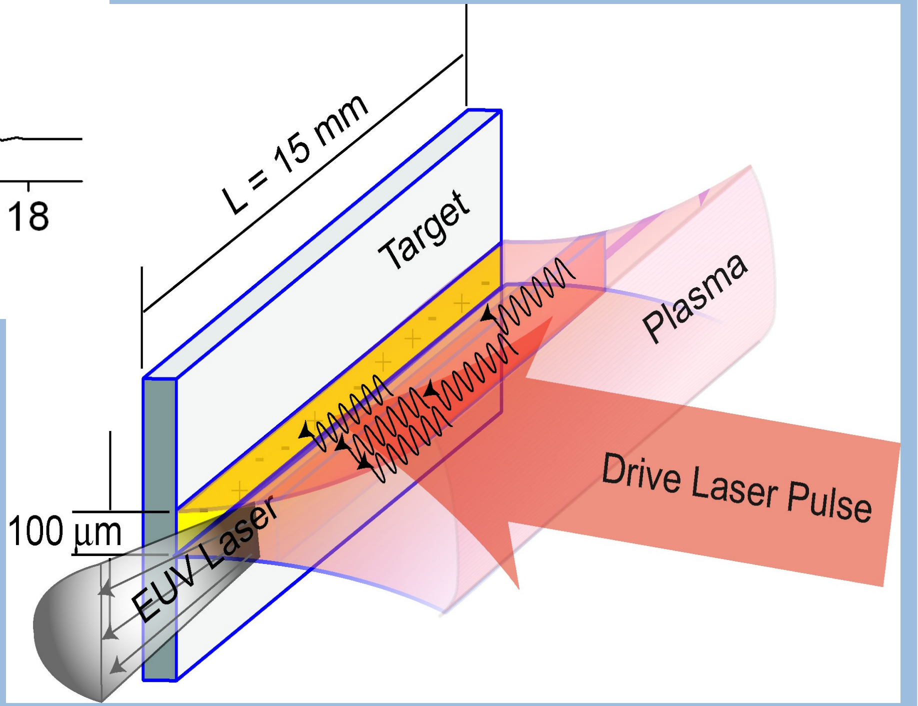

Sn planar target

- Lasing at λ=11.97 nm
- Energy up to 10 uJ
- 2.5 mrad collimation
- Full temporal coherence

The "BeAGLE" Table-top Source
Bern Advanced Glass Laser for Experiments

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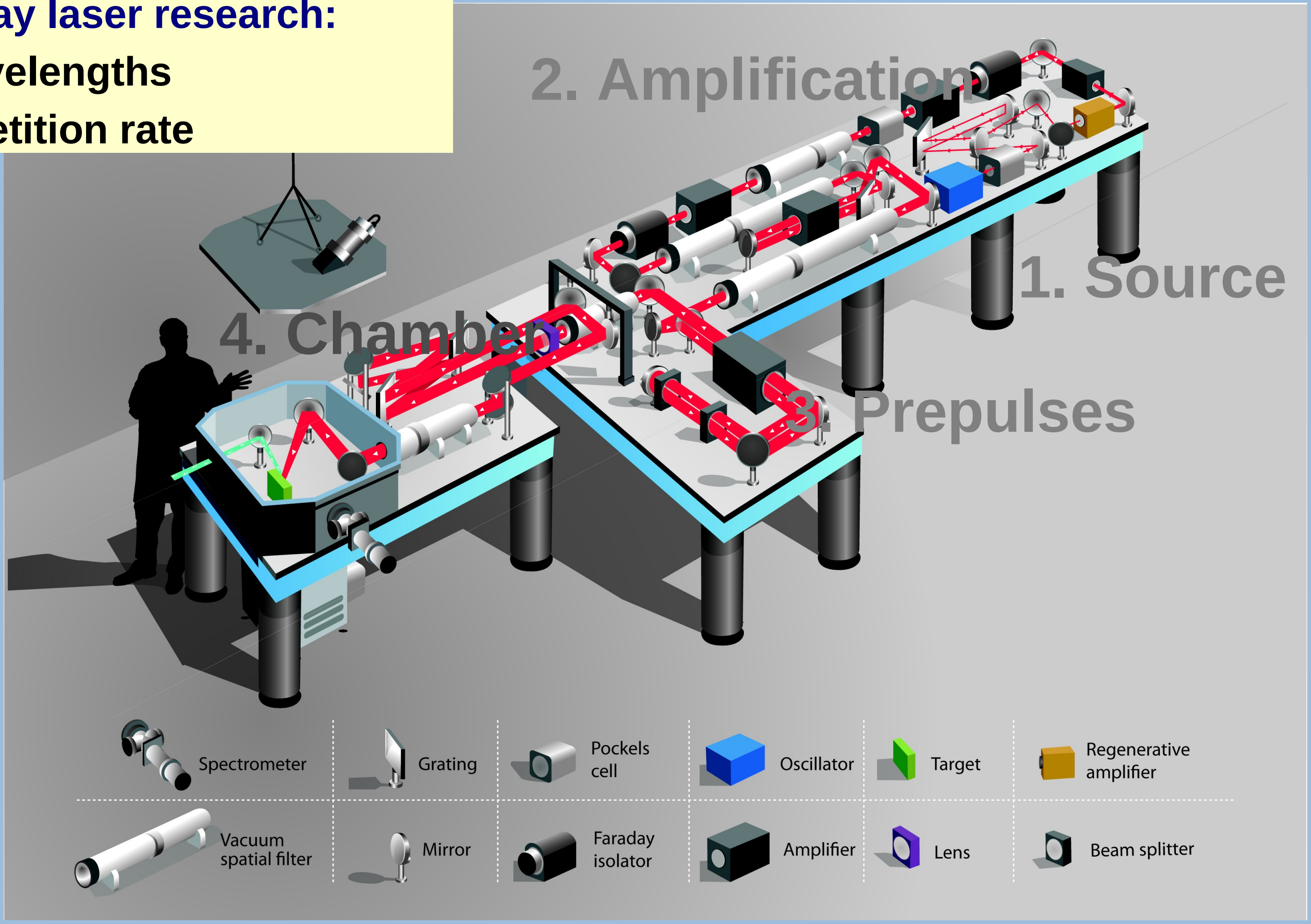
> **Aims of our X-ray laser research:**
- **Shorter wavelengths**
- **Higher repetition rate**



Update on the Lasing Wavelength

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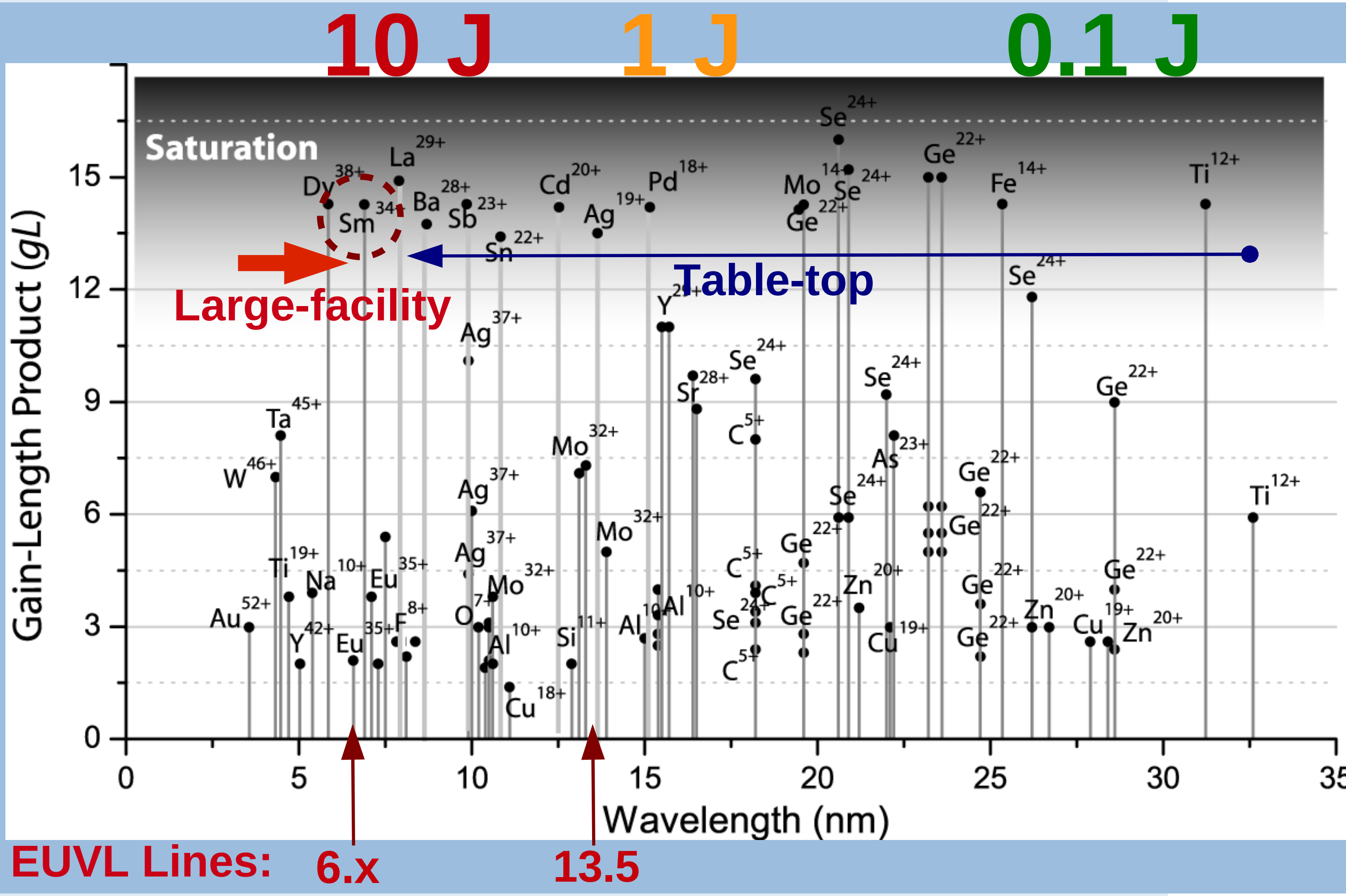

Roadmap on Wavelength Downscaling

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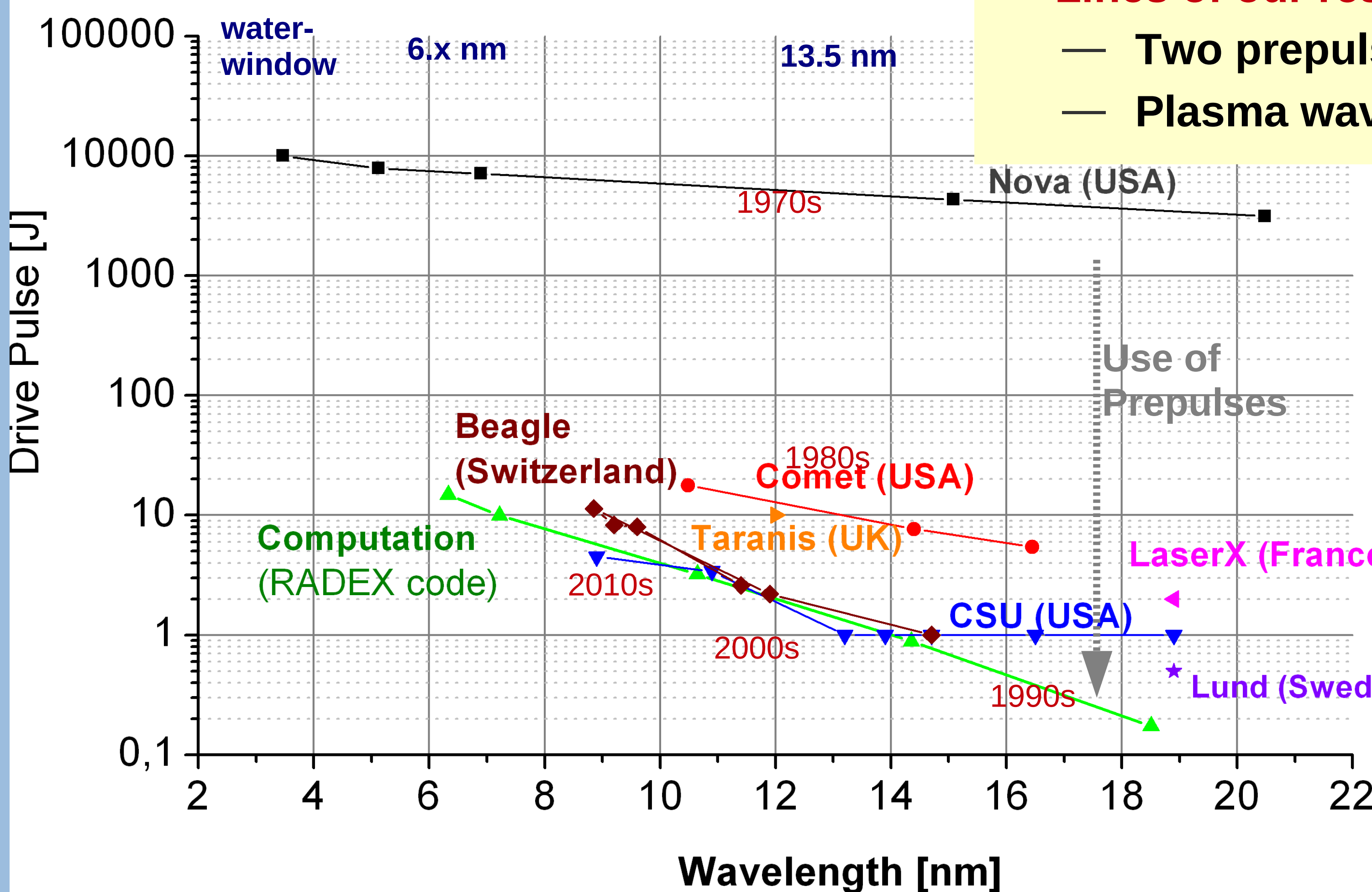
> **Lines of our research:**
> — **Two prepulses**
> — **Plasma waveguiding**



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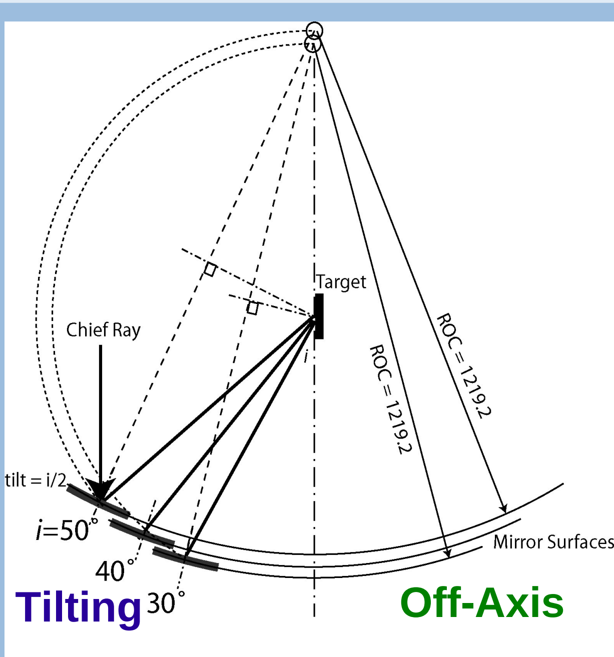
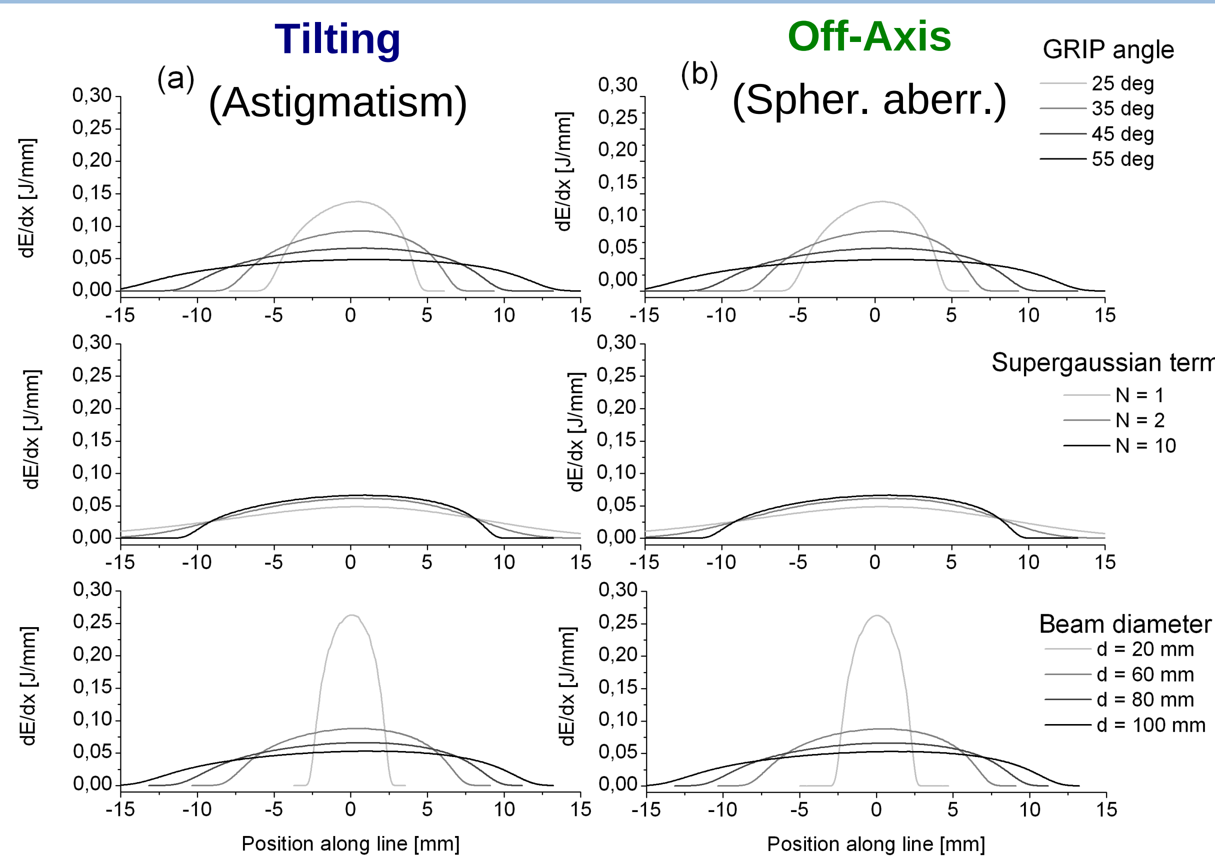
Parametric Study of Mirror Line Focusing





.[a] $I(r)=I_o\exp[-2(r/r_o)^{2N}]$

Benchmarking Our Code with Experiment

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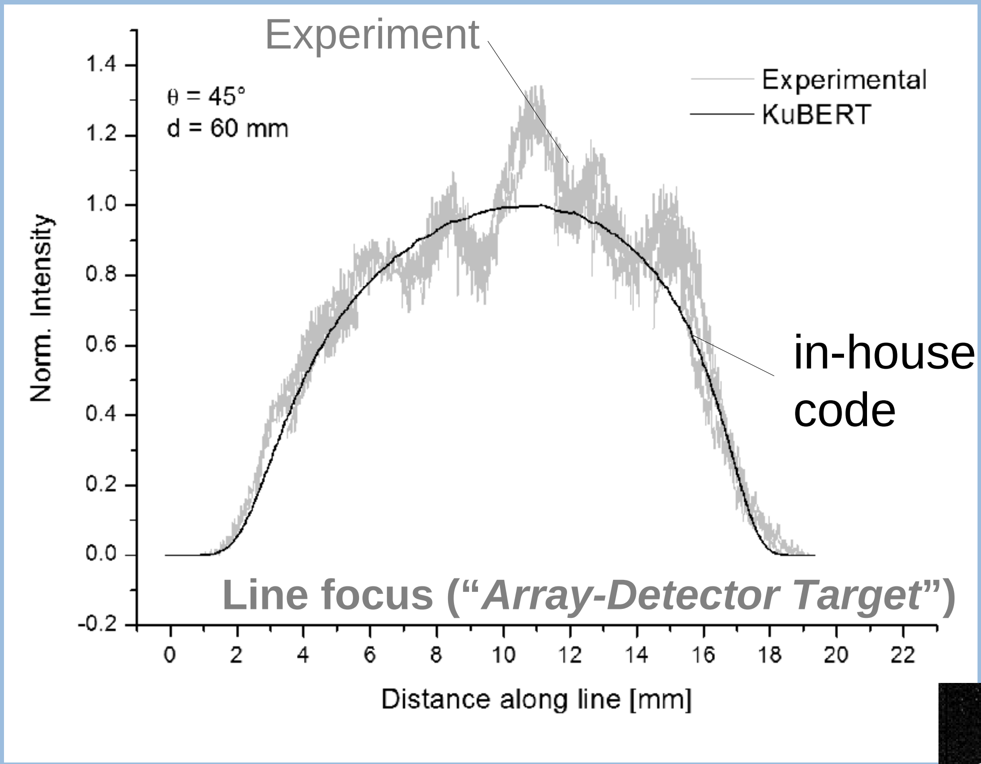

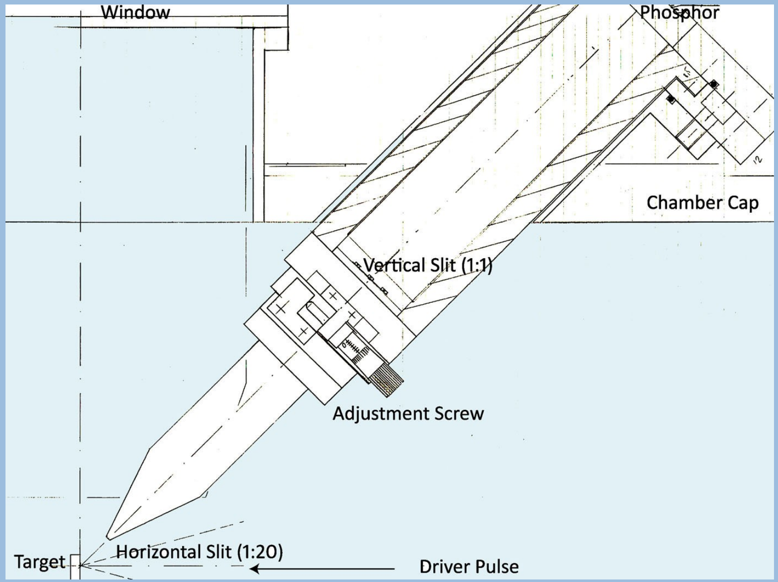

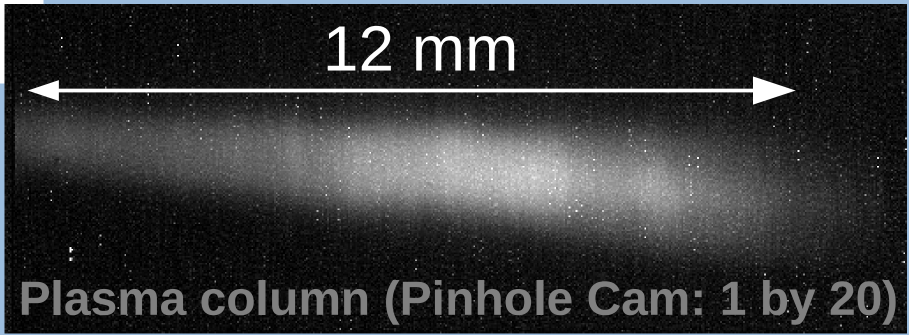

Benchmarking Our Code with Experiment

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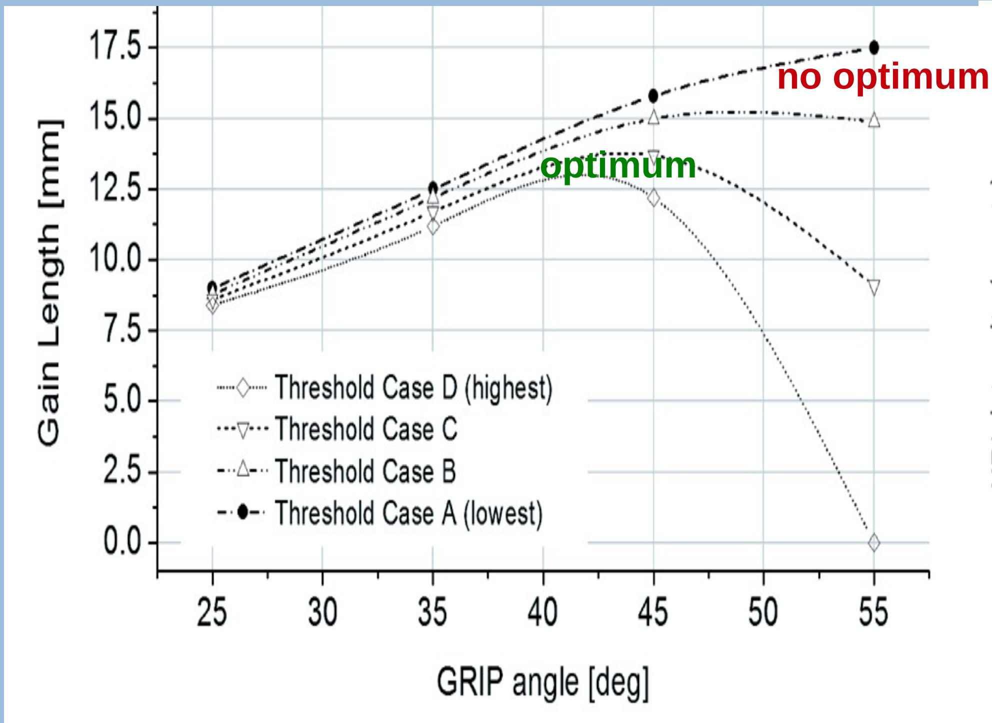
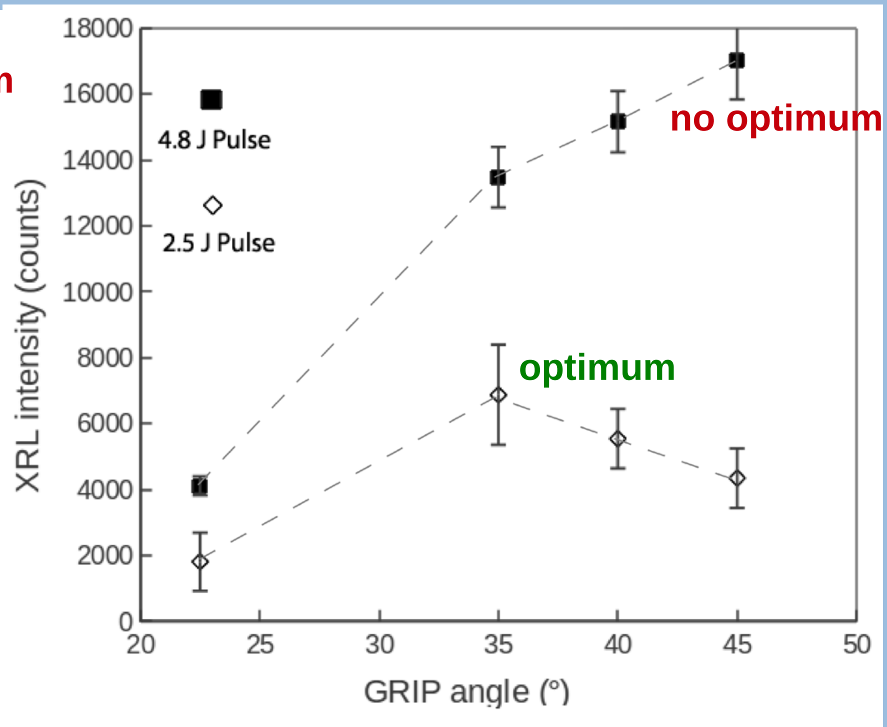
Computation



Experiment



- **Lasing threshold determines the occurrence of an optimum**

ASE Length vs. Grazing Incidence Angle

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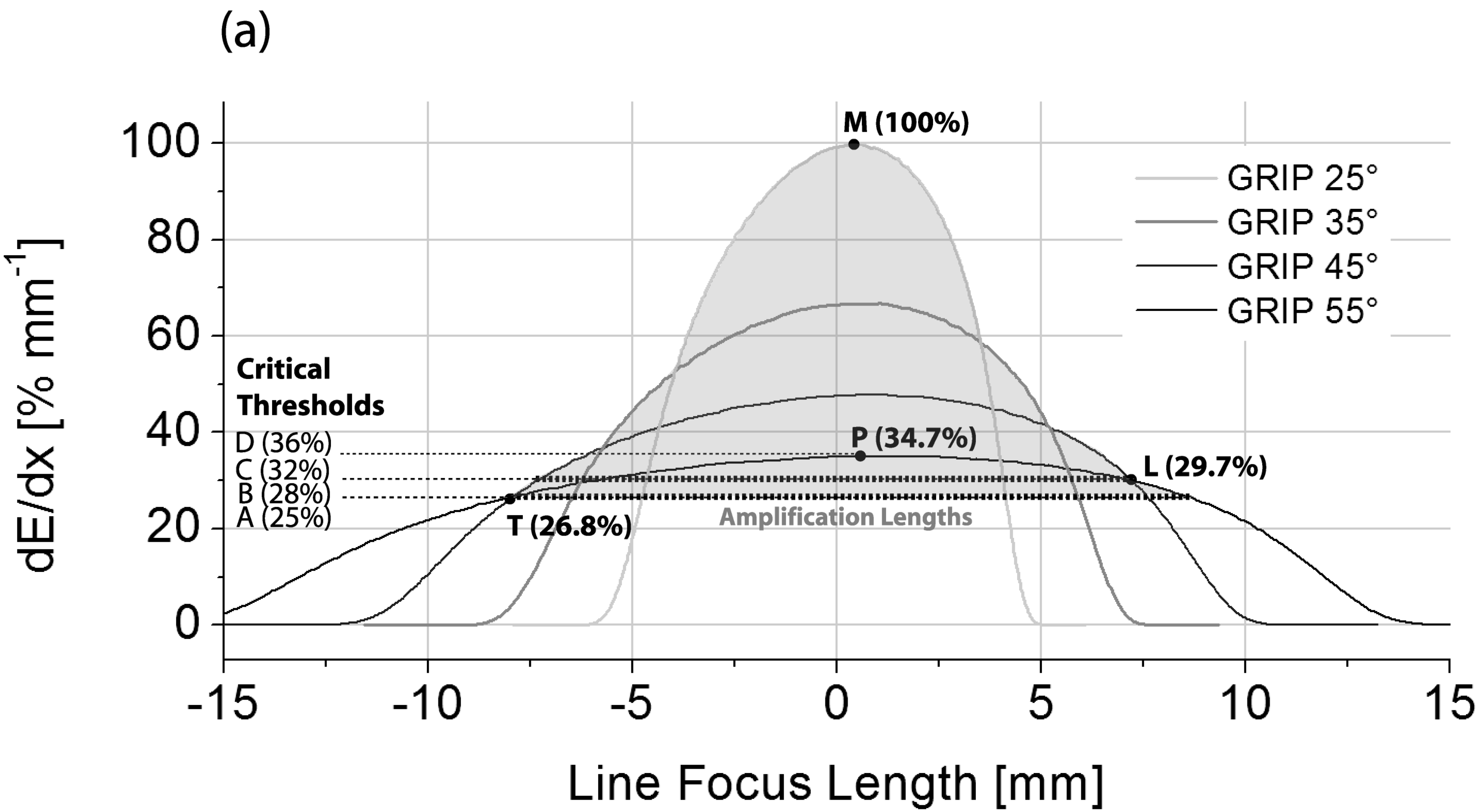

Refraction across the amplification length

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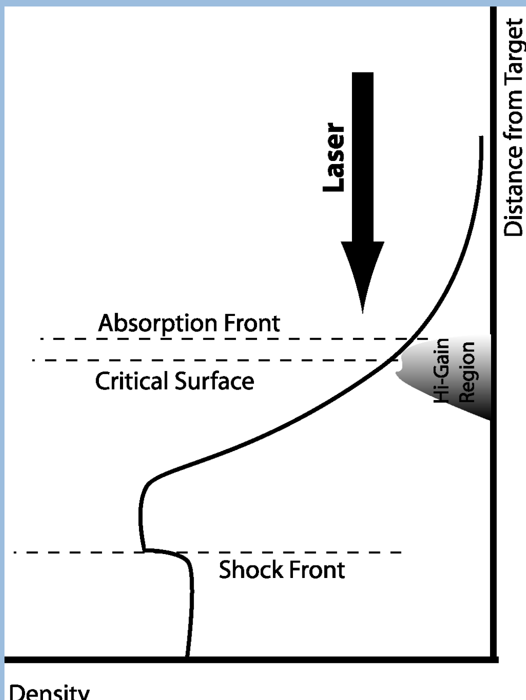
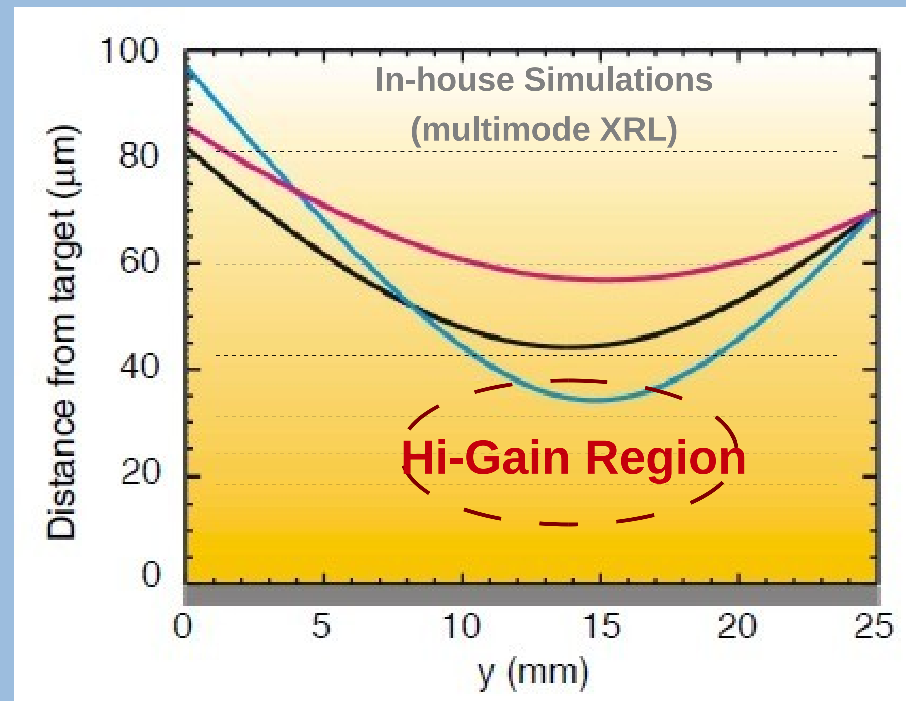


Refractive Index

Density

$$n = (1-\rho_e/\rho_{ec})^{0.5}$$



- The refractive index decreases as density increases.
- In a steep density gradient strong bending occurs away from hi-gain region.

Target Designs for Plasma Wave-guiding

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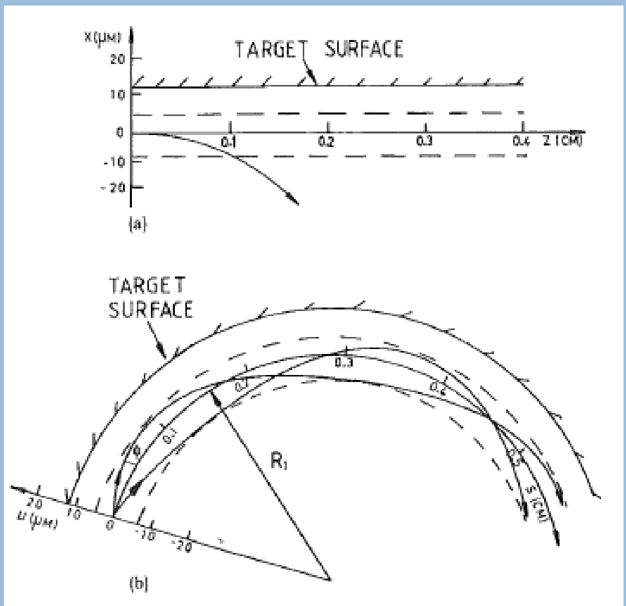
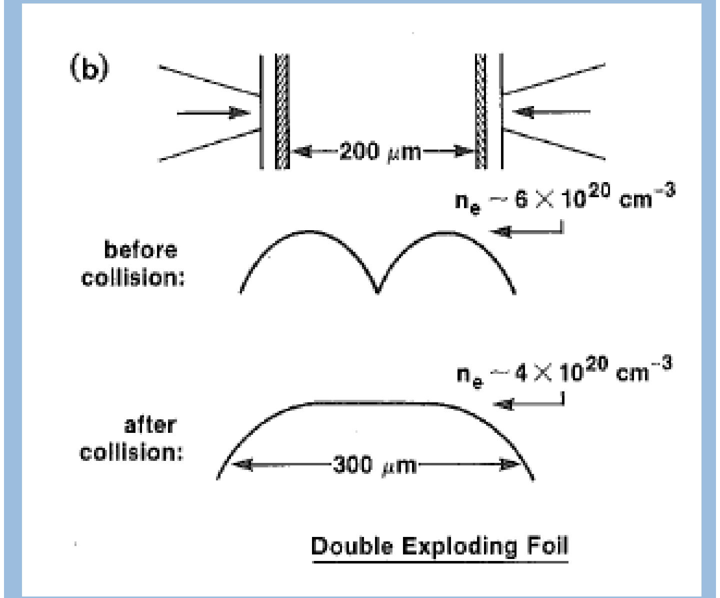
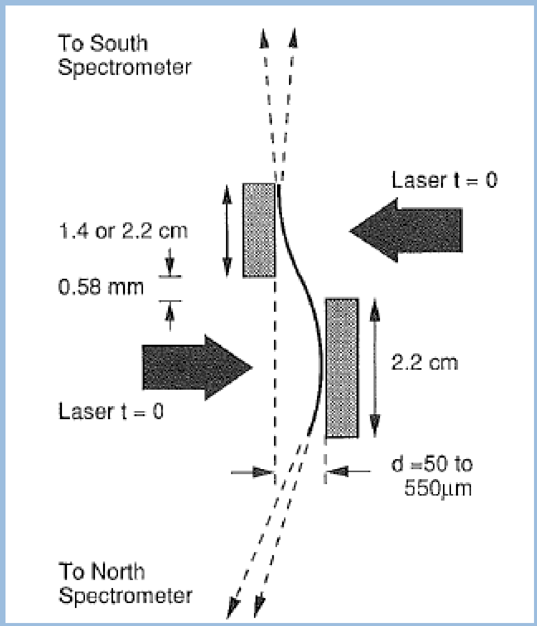


Lunney, Appl. Phys. Lett. 48, 891



Boehly *et al*., Appl. Phys. B 50, 165



Lewis *et al*., Opt. Comm. 91, 71

Bent Slab

Curvature must match refraction in plasma

Double Exploding Foil

Single-Shot Operation

Juxtaposed slabs

Alignment must match refraction in plasma

The Bern Waveguide Targets

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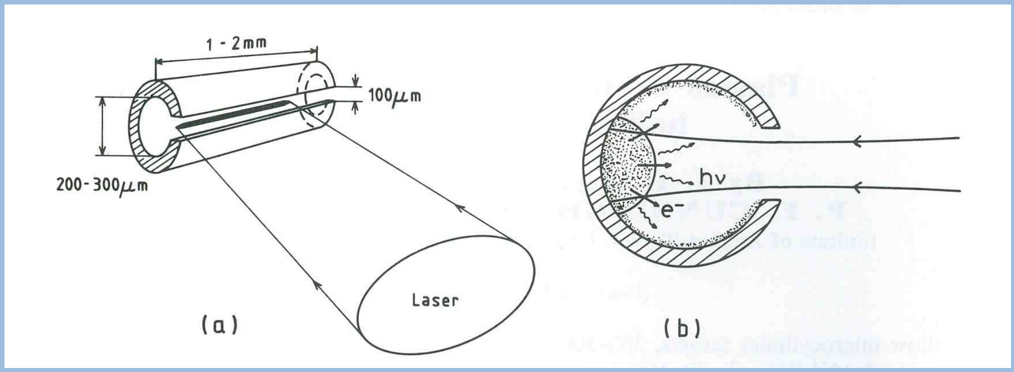
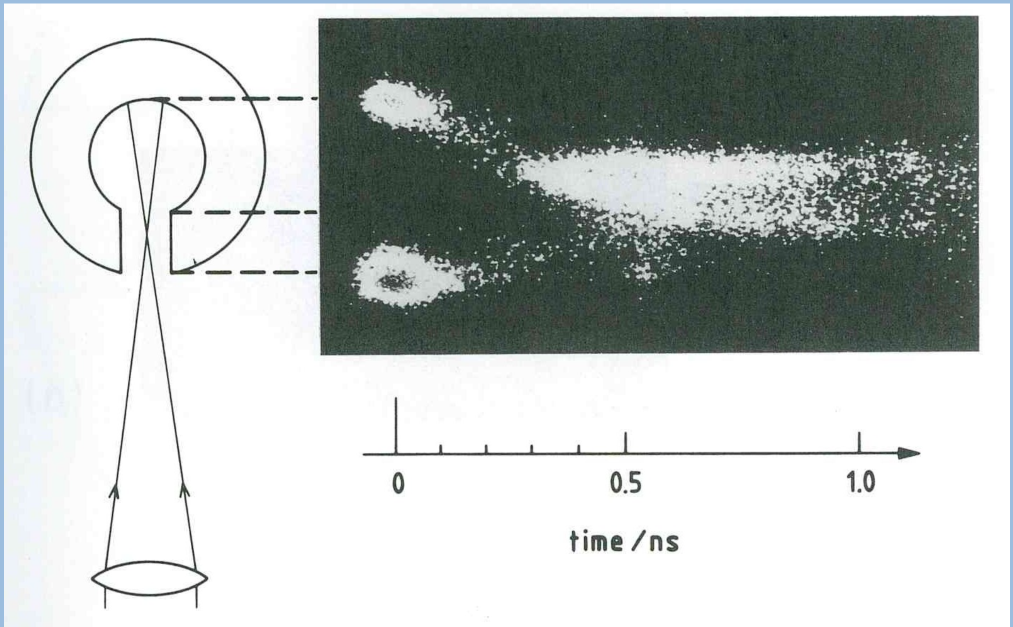
> **Benefits:**

- Induce a <u>concave</u> refractive profile for wave-guiding the EUV beamlets.
- Plasma re-ignition to sustain hot gain zone lifetime
- Trapping driver beam to improve conversion efficiency.





Balmer *et al.*, Laser Part Beams 8, 327

Plasma Wave-Guide: Target Design

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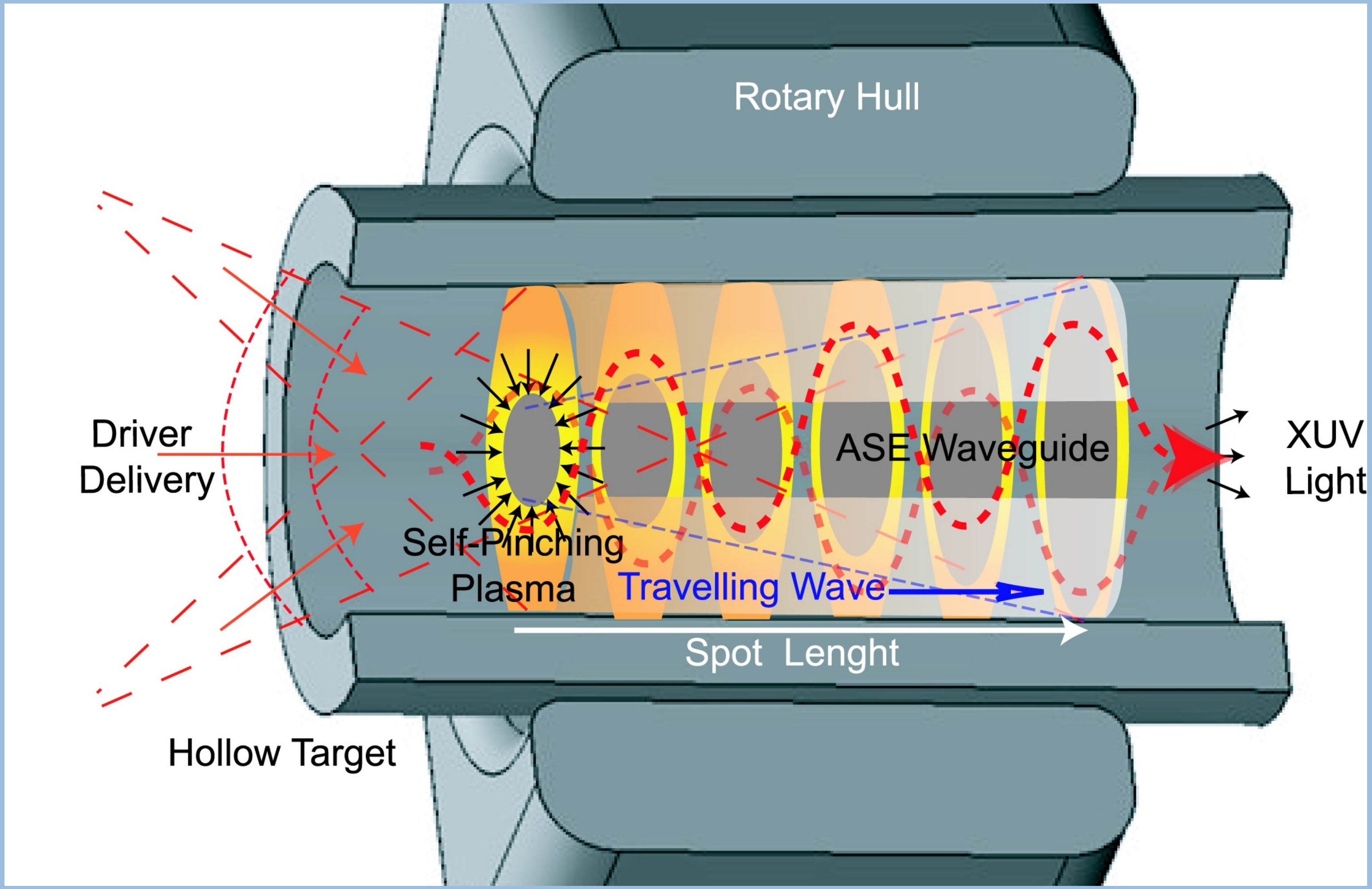

Masoudnia *et al.*, in preparation

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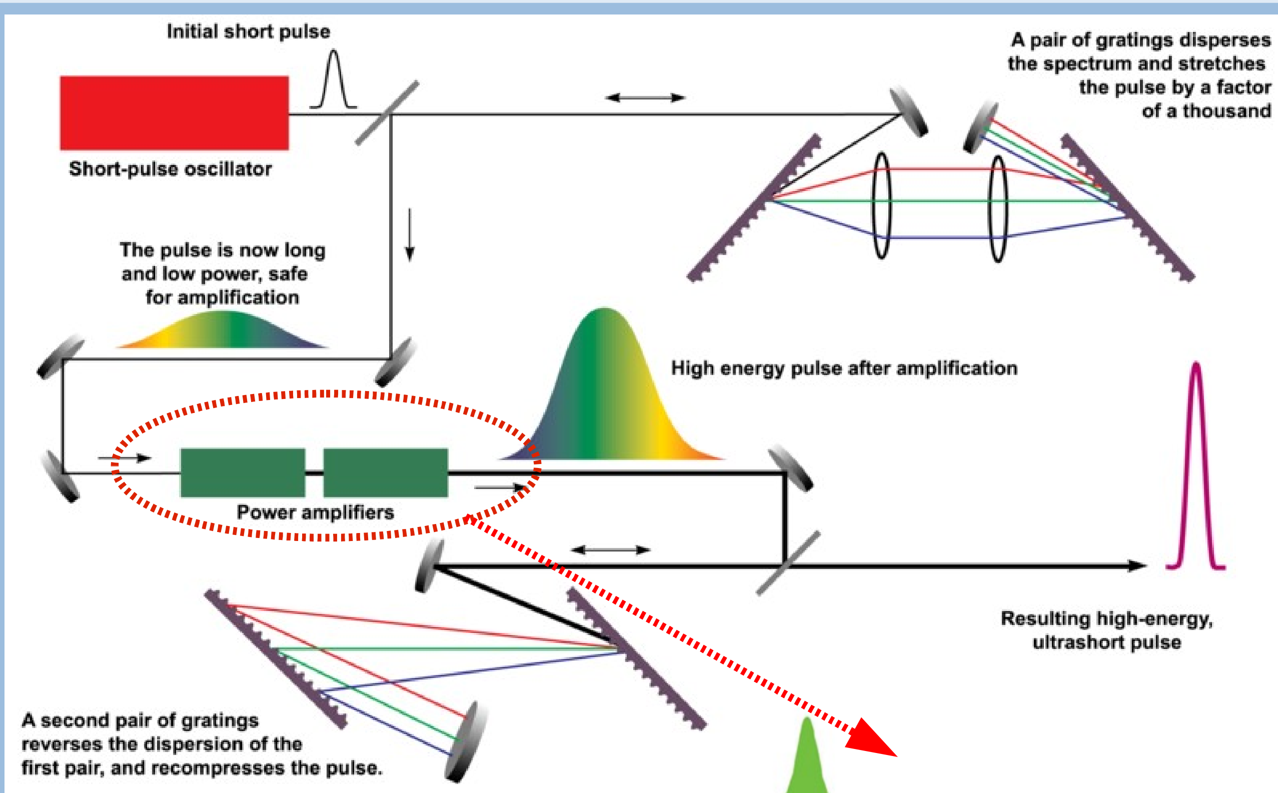
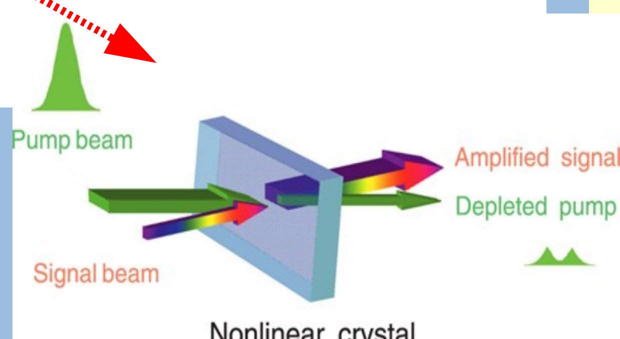
Scaling-up the Repetition Rate





> **Using Opt. Ampl.:**
- Small $\Delta\lambda$
- Heat is stored in the amplifiers
- Limited rep. rate scalability

> **Using OPA:**
- Flexible $\Delta\lambda$
- No heat generated
- Scalability of rep. rate

The Lab-Scale Tool for EUV Research

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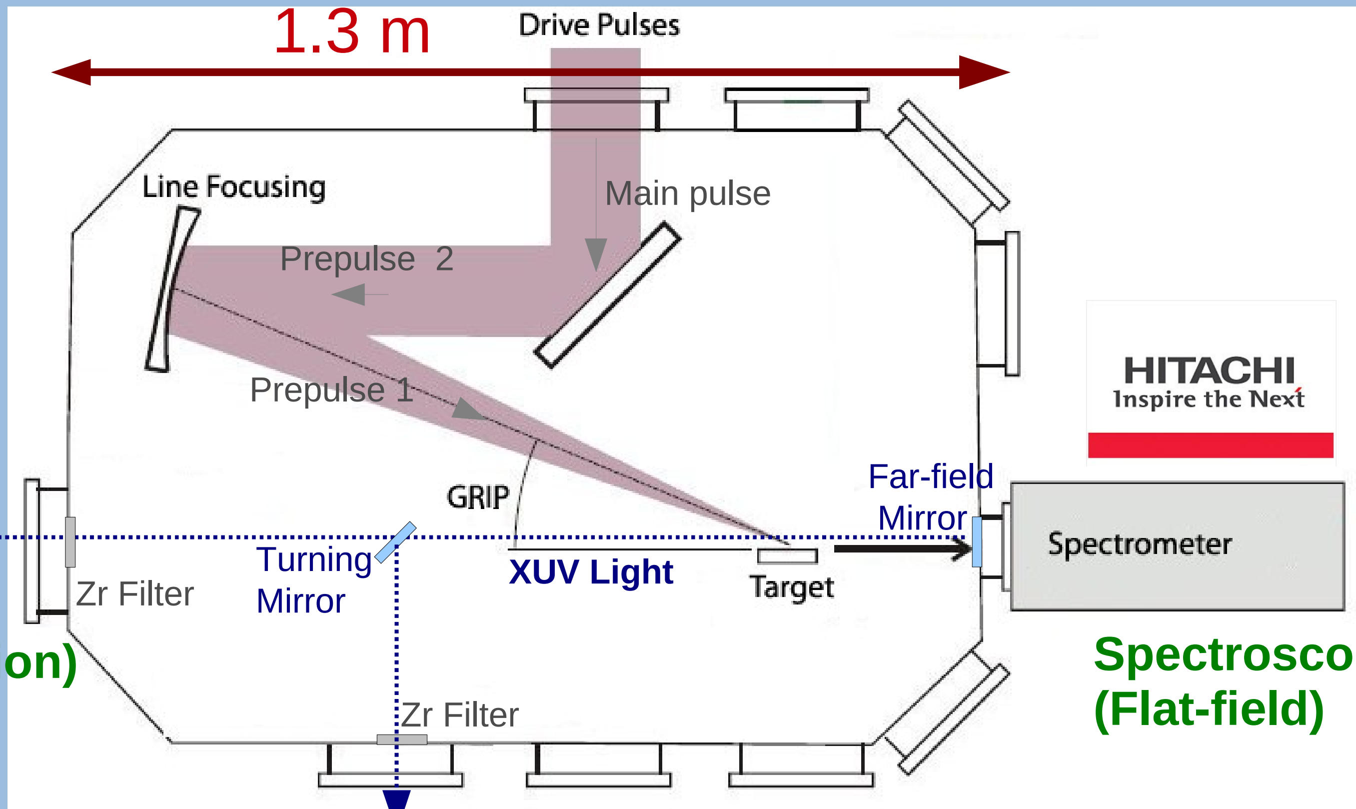
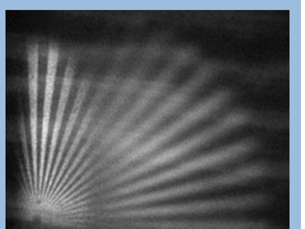
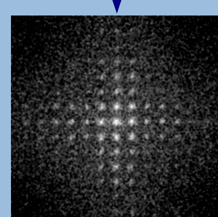




Imaging (Transmission)

Rigaku

Spectroscopy (Flat-field)



Diffraction (Transmission or Reflected, & Polarized Light)

Roadmap for Our Imaging Beamline

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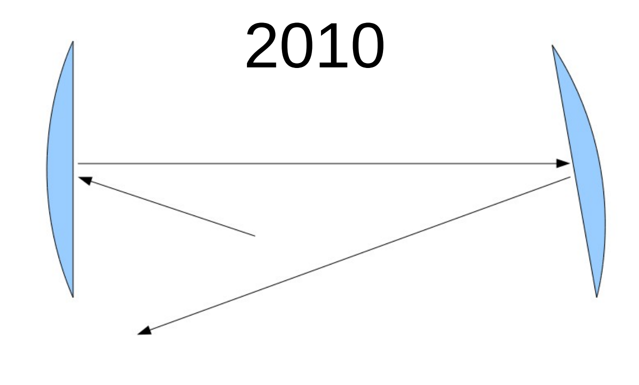

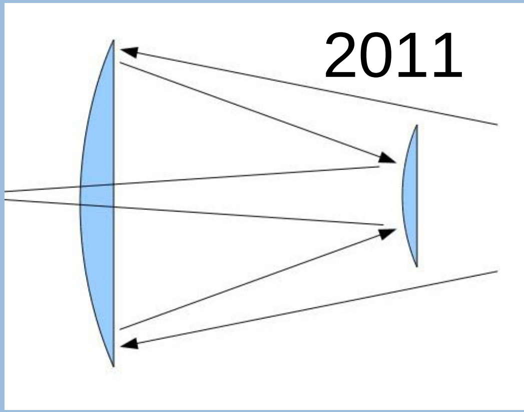

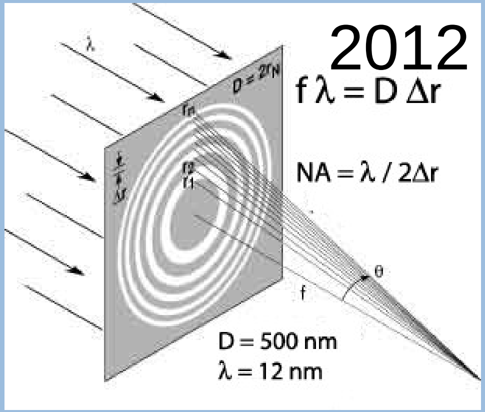

Two-concave Multilayers

- High efficiency (25%)
- Limited to 12x
- Tilt-limited: Astigmatism, Coma

Schwarzschild Multilayers

- Good efficiency (20%)
- Designed for 30x
- No Astigmatism or Coma

Fresnel Zone Plates

- Poor effic. (<10% 1st ord.)
- Available 11x—95x
- Chromatic aberration: XRL has no chromatic dispers.

FNSNF Fonds national suisse / Schweizerischer Nationalfonds / Fondo nazionale svizzero / Swiss National Science Foundation

Rigaku

Paul Scherrer Institut PSI

Two-Concave Multilayers Project (2010)

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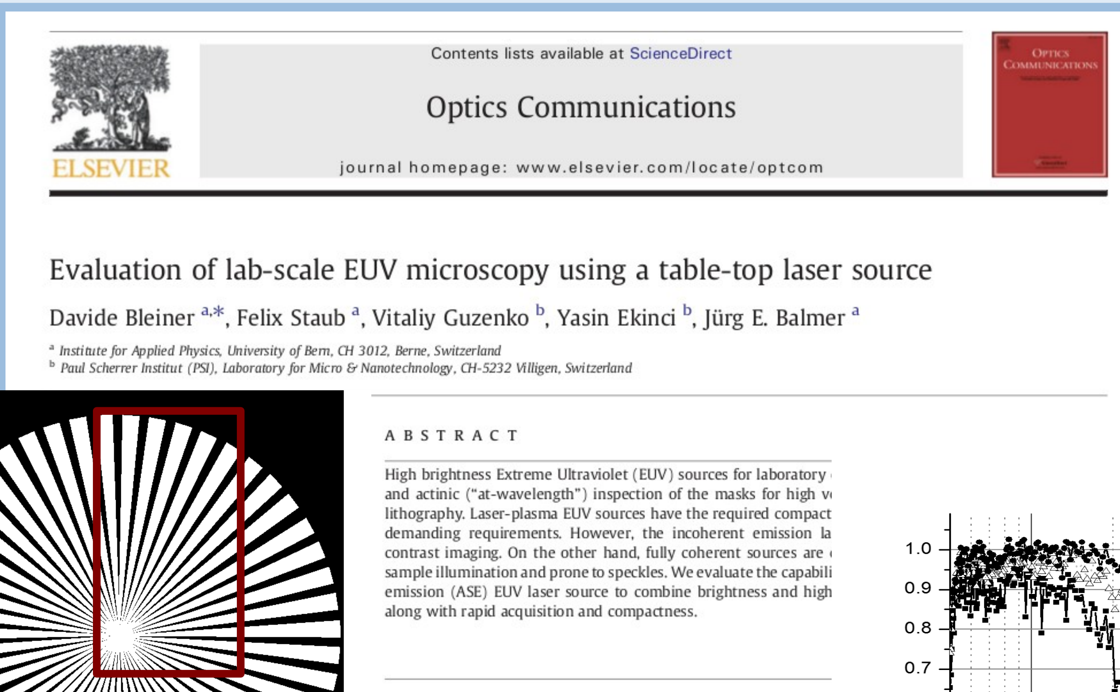

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Evaluation of lab-scale EUV microscopy using a table-top laser source

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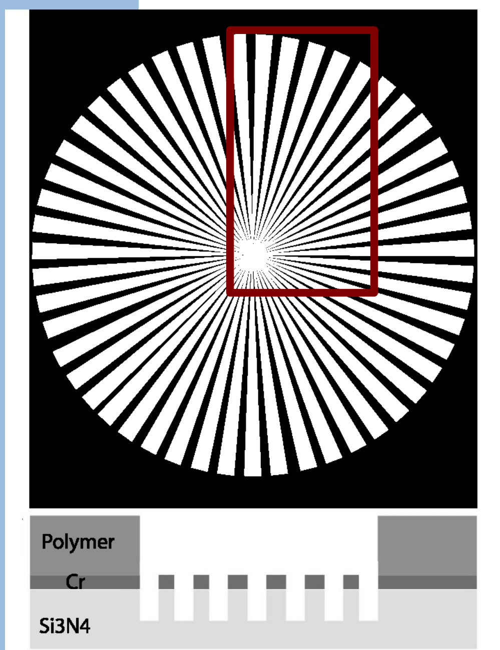
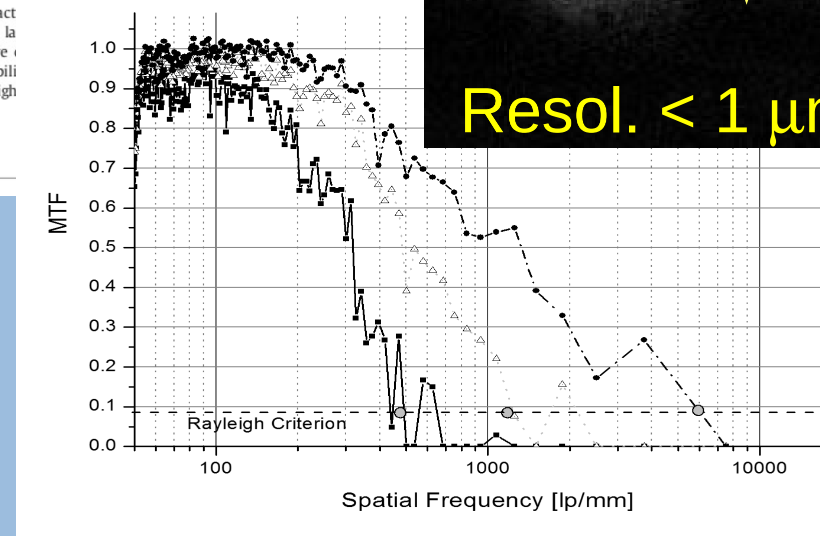
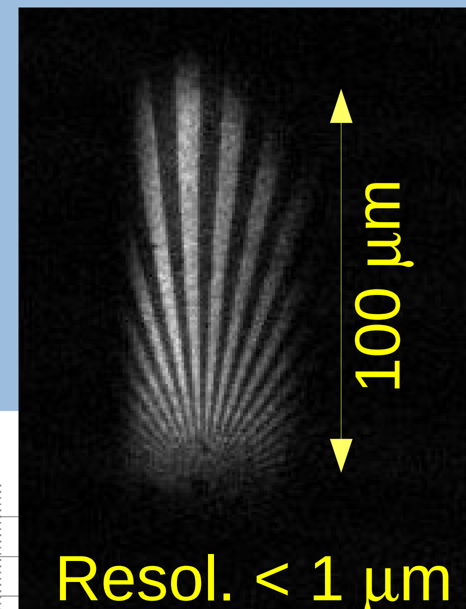
ABSTRACT

High brightness Extreme Ultraviolet (EUV) sources for laboratory
and actinic ("at-wavelength") inspection of the masks for high v
lithography. Laser-plasma EUV sources have the required compact
demanding requirements. However, the incoherent emission la
contrast imaging. On the other hand, fully coherent sources are
sample illumination and prone to speckles. We evaluate the capabili
emission (ASE) EUV laser source to combine brightness and high
along with rapid acquisition and compactness.







Roadmap for Our Diffraction Beamline

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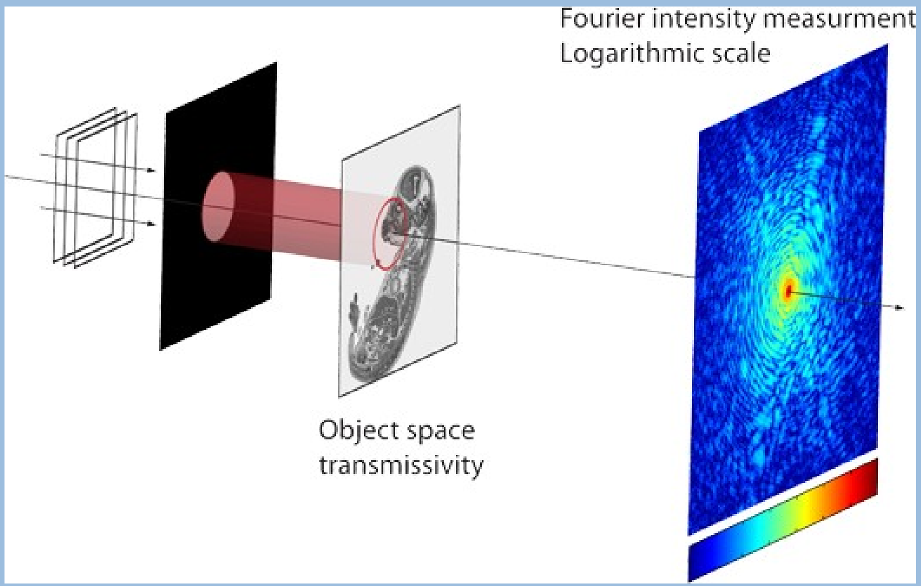
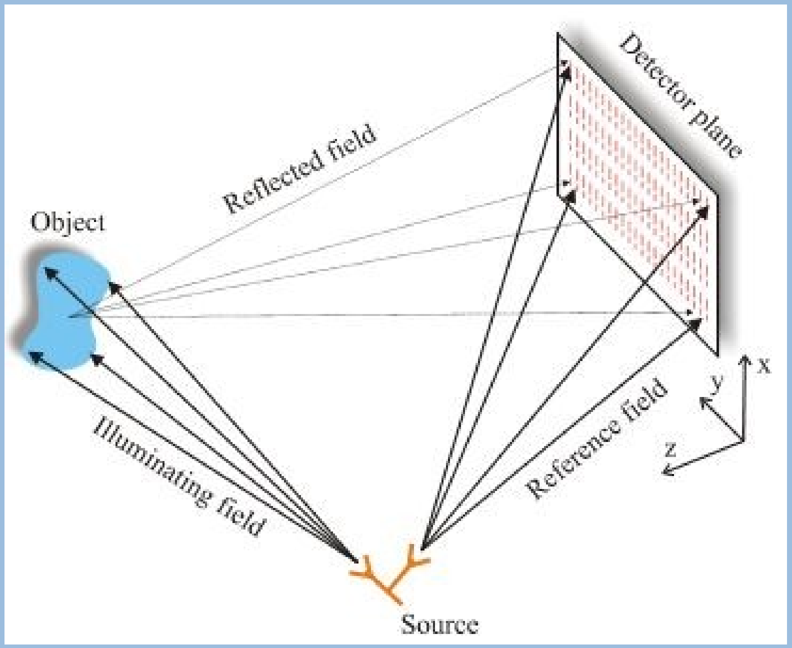
- **Single Beam (2011/12)**
  - Inverse FFT



- **Holography (2012/13)**
  - Phase-Modulation



- Overcome the cost and aberrations of short-wavelength optics;
- Enhanced resolution at low nano-scale.

Ruiz-Lopez *et al.*, in preparation

Test Diffraction Experiments (Fiducial Sample)

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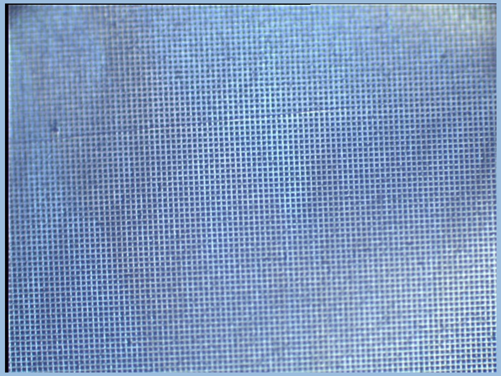
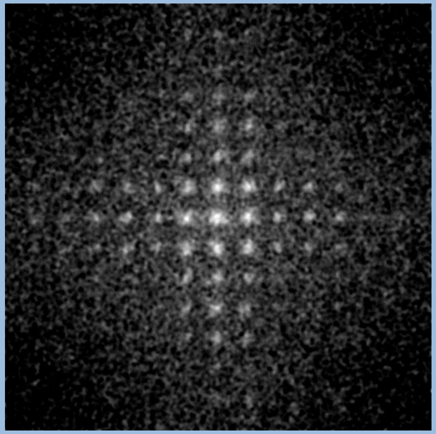
Optical Image 10x

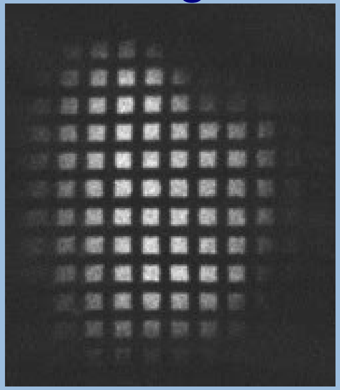


Diffraction Pattern



Pattern Processing

EUV Image 12x



Compare

Inverse FFT

Bridging the Gap Tools-Applications
Summary

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- **X-ray Laser meets the requirements for applications.**

- **Source upgrade by means of:**
  - Optimized grazing-incidence prepulse delivery;
  - "Plasma waveguide" target design allows CE enhancement;
  - Optical parametric amplification allows to scale-up rep. rate;

- **Table-top facility integration has led to:**
  - Spectroscopy beamline;
  - Imaging beamline ("*actinic mode*") in transmission mode;
  - Diffraction beamline ("*lensless imaging*") in transmission or reflective mode;
    - Additionally polarized EUV light capability.

- **What's next?** Migrating Applications from Large-Scale Facility to the Lab.

Acknowledgements

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- **University of Bern co-workers:** Th. Feurer, P.F. Cunningham, U. Ellenberger, A. Glinz, M. Grunig, Ch. Imesch, P. Lädrach, B. Locher, B. Soom, R. Weber, M. Binggeli,
- **Swiss National Science Foundation**
- **Holcim Stiftung Wissen**
- **Rigaku Innovative Technology**